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Analysis

The potential impacts of climate change on capital in the 21st century☆

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ABSTRACT

An endogenous growth model with a simple climate system is used to examine the potential impacts of climate change on the capital-to-net income ratio and the net of depreciation share of income to capital, a measure of wealth concentration and income distribution between capital and labour respectively, over the next two centuries. If climate change only directly affects production, as usually assumed, the capital-to-net income ratio will increase as compared to what it would be in the absence of climate change. The capital-to-income ratio will increase even further if climate change affects labour productivity. In both cases, the increase in the ratio after 2100 is due to the stock of capital being depleted at a lower rate than net income is falling. However, the capital-to-net income ratio will be lower and eventually fall if damage from climate change increases the depreciation rate of capital; this decline is marginally reduced if climate change impacts both capital and labour productivity. In the case where climate change impacts the depreciation of capital, the ratio after 2100 is falling because the stock of capital is destroyed faster than net-income is falling. Furthermore, climate change reduces the net share of income accruing to capital in all scenarios with dramatic changes in the case of climate change affecting the depreciation of capital. Emissions abatement almost completely mitigates these impacts on the capital-to-net income ratio and the net share of income to capital.

1. Introduction

Recently Piketty (2013) and Piketty and Zucman (2014) have examined the capital-to-net income ratio over the past three centuries and made projections into the future. Over the last 30 years this ratio has increased to the high levels observed in Europe during the 1700–1900 period. According to Piketty and Zucman (2014), a higher capital-to-net income ratio "can go together with large instability, asset price bubbles, and high degrees of inequality" (p. 1266). Furthermore,

> Because wealth is always very concentrated…, high β [capital-to-income ratio] implies that the inequality of wealth, and potentially the inequality of inherited wealth, is likely to play a bigger role for the overall structure of inequality in the twenty first century than it did in the postwar period.
>
> Piketty and Zucman (2014, p. 1261)

Piketty (2013) uses the Solow model to demonstrate his Second Fundamental Law of Capitalism: That the steady state capital-to-net income ratio (k/y^{net}) will increase with increases in the net savings rate (s^{net}), and decrease as the long run growth rate of income declines. Along a steady state path, net income is expected to grow at the rate of population growth (n) plus the rate of growth of labour augmenting technological progress (g). As population growth is projected to decline in the future, the capital-to-net income ratio would increase. Furthermore, if productivity growth continues to slow, the ratio would increase further. According to Piketty, the value of world private capital divided by net world income in 2010 was 4.4. And he projects world private capital to be equivalent to almost 7 years of net world income[1] by the end of the twenty first century; a level which has not been observed since the start of the industrial revolution.[2]

Piketty's First Fundamental Law of Capitalism proposes that the share of income net of depreciation that accrues to capital owners is equal to the real rate of return to capital, r, times the capital-to-net income ratio. Piketty (2013) further demonstrates that this net share of

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[1] Piketty (2013) often refers to values of the capital-to-net income ratio in 'years' to illustrate how many years of current net-income are equivalent to the current stock of capital (wealth).

[2] See page 461 of Capital in the Twenty-First Century.

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income to capital has been increasing since 1975 with a rising k/y^{net}. For rich nations, capital income accounted for between 15 and 20% of national income in 1970, but from 2000 to 2010 the share was between 25 and 30%. However, Rognlie (2016) finds that this increase is mainly due to the housing sector. Without the real estate sector, the share has been somewhat falling or unchanged with the rise in the capital-to-income ratio.

We use a simple Integrated Assessment Model (IAM), which consists of an endogenous growth model for the world economy and a simple climate system to examine the potential impacts of climate change on the capital-to-net income ratio and the share of income net of depreciation accruing to capital owners. Like Piketty (2013), we make projections for these indicators over the twenty first century and beyond.

In most IAMs (e.g., Nordhaus' DICE model) it is standard to have climate change only affecting the level of production multiplicatively. The standard damage function used in IAMs is quadratic and usually only calibrated for up to 3 °C temperature anomaly (above pre-industrial levels). The common result is that damages are not considered sufficiently severe to require strong immediate action (Tol, 2018). However, the quadratic damage function has been critiqued for not capturing potentially catastrophic impacts at very high temperatures (Ackerman et al., 2010; Weitzman, 2009, 2010). Therefore, we use a highly convex damage function, as proposed by Weitzman (2012) and used by Dietz and Stern (2015), in our model and demonstrate that there is a large climate impact on the two indicators of inequality.

In our Base Scenario (i.e., damages only on current production) simulations, the world capital-to-net income ratio increases to the equivalent of 7.4 years of net-income by 2100 and over 12 years of net-income by 2150, which is an unprecedented level. To place this in perspective, Piketty's projected change was for the ratio to increase at a much slower rate reaching 6.67 by 2100 due to the assumed continued incentives to save and the slowdown of population and productivity growth.[3] The capital-to-net income ratio increases during this century because the stock of capital (wealth) increases at a faster rate than net income; while during the next century when temperature anomaly is very high, the increase in the ratio is due to the stock of capital falling at a slower rate than the fall in net income. This is a result of the convexity of the damage function, i.e., at higher temperatures net income falls substantially relative to the stock of capital. It is as if the stock of capital is being stranded.

In addition, we explore the impact of climate change on labour productivity and the depreciation of capital. Recent empirical research (Dell et al., 2012; Burke et al., 2015; Letta and Tol, 2016; Donadelli et al., 2017; Du et al., 2017) has focused on climate change directly affecting the growth rate of productivity. Furthermore, Fankhauser and Tol (2005) and Stern (2013) have pointed out that climate change may also affect the longevity of the capital stock. Dietz and Stern (2015), Moore and Diaz (2015), and Bretschger and Karydas (2018) have explored both these possibilities within IAMs. Our modeling approach draws on that of Dietz and Stern (2015), but with a very simple climate system from Matthews et al. (2009, 2012).

We consider scenarios where climate change directly impacts the growth rate of labour productivity and/or the depreciation rate of the capital stock. Our simulations show that through both these channels, damages arising from climate change can further affect the capital-to-net income ratio and the net share of income accruing to capital.

Specifically for when climate change affects capital depreciation, the capital-to-net income ratio will rise initially similarly to when climate change only directly impacts production, but starts diverging after 2050, peaking early next century and then falling at a very fast rate. During this century, when temperature anomaly is < 4 °C, net income increases at a slower rate than the stock of capital. However, during the next century net income per person starts falling at a slower rate than the stock of capital is being destroyed and this drives the capital-to-net income ratio to fall below 2010 levels by 2150. From 2100 and beyond the world capital-to-net income ratio is falling at a similar rate to that observed from World War I to the end of World War II.

If damage from climate change instead decreases the rate of productivity growth, climate change causes even larger increases to the capital-to-net income ratio as compared to when climate only directly affects production. It is essential to note that the increase in the capital-to-net income ratio in the earlier part of the next century, beyond 2100, for when climate change only directly affects production or when climate change affects productivity growth, is due to income falling faster than capital (wealth) is falling. When considering a scenario in which climate change affects both productivity growth and the depreciation of capital, the ratio could increase or decrease with climate change, but decreases for our selected parameter values.

In terms of Piketty's First Fundamental Law of Capitalism, even in the absence of climate change the net share of income accruing to capital falls because the share of income paying for depreciation will increase. With climate change damages, the net share of income accruing to capital will fall even further than in the absence of climate change regardless of the way in which climate change affects production. If climate change only directly affects production, the net share of income accruing to the owners of capital falls from 22% in 2010 to 5% by 2150 and by 2200 it is −2.6%, while without climate change it only falls slightly to < 15% by 2150. The most dramatic impact on the net share of income to capital occurs in the case when climate change impacts the depreciation rate of capital.

We also examine the capital-to-net income ratio and the net share of income to capital in response to climate change mitigation. An unconstrained optimal emissions abatement scenario and one where temperature change is constrained to be no > 2 °C are run. In both abatement scenarios, emissions abatement reduces the effect of climate change on the capital-to-income ratio, regardless of the damage channel. The climate change effect on the net income share to capital is also reduced. Ultimately, in both abatement scenarios, the paths of both indicators of inequality are very close to what they would be in the absence of climate change.

In the next section, we present the details of our climate-economy model with endogenous growth, constant elasticity of substitution production, and a simple climate system. In Section 3 we present simulation results for four different possible scenarios of how climate change impacts the economy. In Section 4 we examine the impact of climate change mitigation. In Section 5 some concluding remarks are presented.

2. A simple climate-endogenous growth model

2.1. The model

To identify how climate change will affect wealth inequality, we combine the endogenous growth model proposed by Dietz and Stern (2015) with a simpler representation of the climate system as in Matthews et al. (2009, 2012).

We alter the Dietz and Stern growth model to consider labour augmenting technological progress and a more general constant elasticity of substitution (CES) production function[4] for output Y_t using capital K_t and L_t labour (population) which is multiplied by labour augmenting technology A_t:

[3] Piketty finds for the developed world the stock of capital during 2000–2010 was equivalent to between 5 and 6 years of the net income.

[4] CES production functions and economic growth have been explored previously by Arrow et al. (1961), Barro and Sala-i-Martin (2003), and Klump and Preissler (2000) among others.

$$Y_t = (1 - D_t^Y)\left(\alpha K_t^{\frac{(\sigma-1)}{\sigma}} + (1-\alpha)(A_t L_t)^{\frac{(\sigma-1)}{\sigma}}\right)^{\frac{\sigma}{(\sigma-1)}}, \tag{1}$$

where $0 < \alpha < 1$, σ is the elasticity of substitution with $\sigma = 1$ being the typical Cobb-Douglas production function, and D_t^Y are damages from climate change that destroy a fraction of current production.

Although not incorporated into the base models of the main IAMs, there is little controversy that the depreciation of capital will be affected by climate change (Fankhauser and Tol, 2005; Stern, 2013). Recently, it has been incorporated into the DICE model (Dietz and Stern, 2015; Moore and Diaz, 2015) and endogenous growth models (Dietz and Stern, 2015; Bretschger and Karydas, 2018). It is very conceivable that climate change can affect the durability and longevity of the capital stock. For example, increased temperatures will cause more extreme weather, higher sea levels, and other environmental abnormalities. Such changes can cause permanent damage to capital infrastructure, e.g., the destruction of capital due to powerful weather systems such as major floods in urban areas. Capital will also require more maintenance due to increased wear and tear from being exposed to more extreme weather. Capital could even be stranded if people are required to migrate away from coastal cities due to sea level rise resulting in capital being left behind to depreciate. With temperature increasing, a larger fraction of investment spending will be allocated towards depreciation (and to adaptation measures) than to the creation of new capital.

To allow for these possibilities, we follow Dietz and Stern (2015) and incorporate climate damages into the following difference equation that describes how the stock of capital changes over time

$$K_{t+1} - K_t = I_t - (\delta_K + D_t^K(1 - \delta_K))K_t. \tag{2}$$

The change in the stock of capital at time $t + 1$ relative to time t is equal to gross investment, I_t obtained from savings, sY_t, less the depreciation of capital $(\delta_K + D_t^K(1 - \delta_K))K_t$, where δ_K is the depreciation rate of capital in the absence of climate change and the term D_t^K is the damage caused to the remaining stock of capital from increased climate change. If gross investment exceeds the depreciation of capital, then the stock of capital will increase since $I_t > (\delta_K + D_t^K(1 - \delta_K))K_t$. But as climate change intensifies, the effective depreciation rate, $\delta_K + D_t^K(1 - \delta_K)$, will increase and investment undertaken may decline if income, Y_t, falls with high temperature anomaly.[5] Thus investment will eventually be equal to depreciation in which case the stock of capital will remain unchanged, i.e., all investment will be for the replacement of capital. As temperature anomaly increases further, gross investment, I_t, will move below the depreciation of capital and then the stock of capital will fall over time reducing the world standard of living.[6]

IAMs generally assume that temperature will have no direct impact on productivity growth; however, it is conceivable that this is not the case. For example, heat stress from increased temperatures is expected to reduce labour capacity (Dunne et al., 2013). Furthermore, a warmer climate could increase the likelihood of human conflict (Hsiang et al., 2013) which may negatively affect the quality of political and economic institutions that support productivity growth. There is evidence that temperature affects long run growth rates linearly (Dell et al., 2012; Letta and Tol, 2016; Donadelli et al., 2017) and non-linearly (Burke et al., 2015; Du et al., 2017).

We assume the level of labour augmenting productivity A_{t+1} is endogenous and is defined following Dietz and Stern as

$$A_{t+1} = (1 - D_t^A)(1 - \delta_A)A_t + \gamma_1 I_t^{\gamma_2}. \tag{3}$$

Like Dietz and Stern we assume that labour productivity depreciates at slower rate, δ_A than the stock of capital. This rate could be positive or negative as there are two counterbalancing effects operating. Productivity depreciates due to wear over time of the acquired skills and knowledge but could be offset with institutional innovations such as within-firm labour flexibility practices and the quality of government services (Preenen et al., 2017; Balzs, 2016). In our model, the damage function, D_t^A, in Eq. (3) is used to model the direct impact of climate change on productivity growth. Damages represented by D_t^A increases the effective depreciation rate of labour productivity. If productivity was only depreciating through time as shown by the first term in Eq. (3) then the world standard of living would be falling, but the second term in Eq. (3), namely $\gamma_1 I_t^{\gamma_2}$, introduces endogenous growth to the model for sustained growth as in Dietz and Stern (2015). This part of labour productivity growth is meant to represent knowledge externalities (i.e., spillover benefits) from the undertaking of new investment including human capital investment and research and development (Barro and Sala-i-Martin, 2003; Acemoglu, 2008; Dietz and Stern, 2015). We also assume that new investment leads to higher labour productivity but at a diminishing rate and thus $\gamma_1 > 0$ and $0 < \gamma_2 < 1$. Following Dietz and Stern (2015), we calibrate the values of γ_1 and γ_2 to produce similar growth as the model with exogenous growth in A_t in the absence of climate change.[7]

The terms D_t^Y, D_t^K, and D_t^A are related in the following way, similar to Moyer et al. (2014) and Dietz and Stern (2015),

$$D_t^Y = 1 - \frac{(1 - D_t)}{(1 - D_t^K - D_t^A)}, \tag{4}$$

$$D_t^K = f^K D_t, \tag{5}$$

$$D_t^A = f^A D_t, \tag{6}$$

where the terms f^K and f^A assign how much of the impact from climate damages affects the depreciation of the capital stock and growth in technology respectively. In our Base Scenario, these terms are set equal to zero, so that climate damages only directly affect total production. We then consider a Productivity Impact Scenario where $f^A = 0.05$ as in Moyer et al. (2014) and Dietz and Stern (2015). We also consider a Depreciation Impact Scenario where $f^K = 0.3$ and $f^A = 0$ as in Dietz and Stern (2015). In addition, we further consider an All Impacts Scenario where climate damages fall on all three channels and set $f^K = 0.3$ and $f^A = 0.05$.

We use the following convex damage function proposed by Weitzman (2012) and implemented by Dietz and Stern (2015)

$$D_t = 1 - \frac{1}{1 + \theta_1 T_t^2 + \theta_2 T_t^{6.754}}, \tag{7}$$

where T_t is temperature anomaly relative to the pre-industrial level. The standard damage function from the DICE model is similar, but has $\theta_2 = 0$ calibrated for temperature anomaly mostly in the 2 °C–3 °C range (Tol, 2018). However, temperature anomaly above 3 °C may

[5] A higher savings rate might offset the impact on savings from the potential reduction in income but in this model we assume a constant savings rate, as in Dietz and Stern (2015). There is no literature that we are aware of which suggests how the savings rate will change with a long term downward change in income due to climate change. Feldstein (2010) argues that America's savings rate declined over a quarter of a century until 2007 because of rising stock market and housing prices. See: https://scholar.harvard.edu/feldstein/publications/americas-saving-surprise.

[6] We follow Dietz and Stern (2015) and assume a constant gross savings rate at 25% which is slightly higher than the Dietz and Stern 23% rate. This is consistent with Piketty (2013) and Fankhauser and Tol (2005). Furthermore, the Nordhaus 2016 DICE model finds a gross savings rate from 2015 to 2510, in 5-year intervals, at an average savings rate of 24.7% with maximum rate in 2015 at 26% and the lowest rate from 2085 until 2135 at 24%. Also, as stated by Dietz and Stern (2015), "in any case, whether households are currently taking into account the effects of climate policy on future consumption prospects when choosing how much to save is unclear." (p. 593).

[7] The exogenous rate of growth of A_t for the calibration is taken from the 2013 DICE model.

cause severe damages for which the quadratic formulation cannot capture. The value of θ_2 and the exponent of 6.754 has been calibrated by Weitzman (2012) for a 50% output loss when temperature anomaly is 6 °C above pre-industrial levels. High temperature anomaly can result in the system passing the tipping point at which severe irreversible damages may occur (see Lenton, 2011; Stern, 2013; Lontzek et al., 2015; Lemoine and Traeger, 2016).[8] Dietz and Stern (2015) show that using this highly convex damage function justifies global efforts to reduce emissions to keep temperature rise below 2 °C, whereas the DICE damage function suggests these efforts are not net-beneficial. Bretschger and Pattakou (2019) also find that highly convex climate damages justify aggressive mitigation. In Appendix A we report results using the standard DICE damage function in our model; using the DICE damage function does not change the overall direction of our results, but does substantially dampen the magnitude of the impacts.

Carbon emissions, E_t are assumed to be proportional to total production, Y_t

$$E_t = \mu_t Y_t \tag{8}$$

where $\mu_t \geq 0$ is emissions intensity. Following Nordhaus and Sztorc (2013), emissions intensity is exogenous and declines over time at an increasing rate (e.g., the growth rate of μ is given by $\pi_t = \pi_{t-1}/(1 + \delta_\mu)$, in which $\pi < 0$ and $\delta_\mu < 0$).

The climate portion of the model uses the Carbon Climate Response or transient climate response to cumulative carbon emissions, a proportional, stable linear relationship between cumulative emissions and global temperature change (Matthews et al., 2009; Matthews et al., 2012; MacDougall and Friedlingstein, 2015; Tokarska et al., 2016) given by

$$T_t = \beta\left[C_0 + \sum_{i=1}^{t-1} E_i\right]. \tag{9}$$

The first term of Eq. (9), β, is the Carbon Climate Response parameter and the second term is cumulative emissions to year t (C_0 is cumulative emissions prior to the base year). The relationship has been shown to hold for both historical data and the projections from climate models (Matthews et al., 2009; Matthews et al., 2012). The linear relationship found in climate models is due to offsetting carbon and climate sensitivity feedbacks (MacDougall and Friedlingstein, 2015). Tsigaris and Wood (2016) also use this climate carbon response function to create a simple climate-Solow model. Taylor (2014) combines the Solow model with a similar carbon budgeting relationship to assess the feasibility of meeting the 2 °C target by reducing carbon intensity alone. More recently, the relationship has been used by Dietz and Venmans (2018), Moreno-Cruz et al. (2018), and Vogt-Schilb et al. (2018) to simplify climate-economy modeling.

2.2. Capital-to-income ratios

The version of the Solow model that Piketty uses differs from the standard "textbook" version in that he assumes a constant rate of net savings, s^{net} rather than a constant rate of gross savings, s.[9] His model has the following dynamic path of the capital stock: $K_{t+1} = K_t + s^{net} Y_t^{net}$ where $Y_t^{net} = Y_t - \delta_K K_t$ is net output and $s^{net} = s - \delta_K$ is the net savings rate. Piketty's capital-to-net income ratio in a steady state is[10]:

$$\frac{k}{y^{net}} = \frac{s^{net}}{(n+g)}. \tag{10}$$

Piketty projects that this ratio will increase in the future as population growth and productivity growth decline.

The way in which we calculate k/y^{net} is different than Piketty. Since we have T_t changing over time and endogenous growth in A_t, we do not focus on the steady state ratio as Piketty does. Instead we calculate the k/y^{net} ratio at each time period as the following

$$\frac{k_t}{y_t^{net}} = \frac{k_t}{(y_t - \delta_k k_t)}, \tag{11}$$

where y_t and k_t are the simulated values of income per capita and capital per capita from our simulations at each time period.

2.3. The net share of income to capital

Piketty's First Fundamental Law of Capitalism is associated with the pattern over time of the net share of income that accrues to capital. Piketty expresses the First Fundamental Law of Capitalism as the net capital share of income equal to the real rate of return to capital, r, times the capital-to-net income ratio. Under profit maximization and competitive capital markets the marginal productivity of capital net of the depreciation rate, $(MP^k - \delta_k)$, is equal to the real rate of return to capital, r. Using $(MP^k - \delta_k)$ as a substitute for the real rate of return to capital, the income accruing to capital net of depreciation as a fraction of net-income is $(MP^k - \delta_k)\left(\frac{k}{y^{net}}\right)$. The marginal productivity of capital is

$$MP_t^k = \alpha(1 - D_t^Y)^{\frac{(\sigma-1)}{\sigma}}\left(\frac{k_t}{y_t}\right)^{-\frac{1}{\sigma}}, \tag{12}$$

and the net share of income that accrues to capital at time, t is thus

$$\text{Net Share}_t = \left[\alpha(1 - D_t^Y)^{\frac{(\sigma-1)}{\sigma}}\left(\frac{k_t}{y_t}\right)^{-\frac{1}{\sigma}} - \delta_k\right]\left(\frac{k_t}{y_t^{net}}\right). \tag{13}$$

An increase in the capital to income ratio by 1% will reduce the marginal productivity of capital by $1/\sigma$. If $\sigma > 1$, the gross share of income to capital will increase, but this increase will be more than offset by the increase in the share of income that goes to depreciation charges in order to maintain the capital stock; therefore, resulting in an overall decline in the net of depreciation share of income accruing to capital owners. Piketty in chapter 6 page 220 of *Capital in the Twenty-First Century* argues that in the long run, capital can have many different uses and hence it is easier to substitute labour for capital, i.e., that $\sigma > 1$.[11] When $\sigma = 1$ (the Cobb-Douglas case) the marginal productivity of capital falls by 1%, thus leaving the gross share of income unaffected by the rise in the capital-to-income ratio. However, even in the Cobb-Douglas case the net share of income accruing to capital will fall as the capital-to-income ratio rises because more capital-to-income implies a higher depreciation replacement amount to keep the capital stock intact.

3. Simulation results

3.1. Base Scenario results

We numerically simulate the path of income per person y_t, capital per person k_t, and technology A_t based on Eqs. (1) through (9). We then calculate the capital-to-income ratio, k_t/y_t^{net} as in Eq. (11), as well as

[8] For the origins, precursors and debate on climate change tipping points see Russill (2015).

[9] A constant gross savings rate rather than a constant net savings rate fits better with available data on savings (Krussel and Smith, 2015).

[10] Along a steady state the stock of capital, K, will grow at $n + g$ and thus $(1 + n + g)K = K + s^{net}Y^{net}$. Solving for $\frac{K^{net}}{Y}$ yields $\frac{s^{net}}{n+g}$.

[11] Piketty states on page 221: "One need not to imagine a fully robotized economy in which capital would reproduce itself (corresponding to an infinitely elasticity of substitution) to appreciate the many uses of capital in a diversified advanced economy in which the elasticity of substitution is greater than one."

Table 1
Selected values.

Parameter	Value	Source
α	0.3	Nordhaus and Sztorc (2013)
s	0.25	Similar to Dietz and Stern (2015) (23%) and Nordhaus and Sztorc (2013) (average savings rate is 24.5%)
δ_K	0.02669	Selected to reflect a 5% real rate of return on capital which is within the range of the worldwide equity premium puzzle (Dimson et al., 2008)
L_0	6.916	UN, Dept. of Economic and Social Affairs, Population Division (2013). World Population Prospects: The 2012 Revision. (in billions)
n_0	0.0118	UN, Dept. of Economic and Social Affairs, Population Division (2013). World Population Prospects: The 2012 Revision.
δ_L	0.028	This parameter defines how n_t declines over time. Nordhaus and Sztorc (2013)
A_0	5.5	Residual from the production function.
δ_A	0.01	Depreciation rate for A; Dietz and Stern (2015)
γ_1	0.06554501	Calibrated as in Dietz and Stern (2015)
γ_2	0.4046154	Calibrated as in Dietz and Stern (2015)
y_0	10	Thousand of 2005 USD. Rounded to the world bank national accounts figure of 9.515 2010 USD
k_0	39	Thousand of USD to make the k/y^{net} in 2010 equal to 4.4 as in Piketty
μ_0	0.489	Nordhaus and Sztorc (2013).
π_0	−0.01	Initial growth rate of carbon intensity. Nordhaus and Sztorc (2013).
δ_μ	−0.0002	Defines how π_t becomes more negative over time. Nordhaus and Sztorc (2013).
θ_1	0.002131	Nordhaus and Sztorc (2013).
θ_2	5.0703×10^{-6}	Weitzman (2012).
β	1.8	Matthews et al. (2009).
C_0	530	Gt of carbon. Matthews et al. (2012).
ϕ_0	0.06	Nordhaus and Sztorc (2013).

the net-share of income accruing to capital into the future as in Eq. (13).

Selected initial values for the simulations are displayed in Table 1. Initial values for variables were selected for 2010 as the base year. Parameter values were selected in many cases to match the assumptions in the 2013 DICE model. For our main simulations (displayed in Figs. 1 and 2) we set σ equal to one (i.e., the Cobb-Douglas case), but also explore $\sigma > 1$ and the less plausible case of $\sigma < 1$.

The projections of the Base Scenario for temperature anomaly, income per person and the capital-labour ratio are the red lines displayed in Fig. 1. Temperature anomaly reaches 4.1 °C by 2100 and 6.5 °C by 2200. By 2100, income per capita is 11.8% less than when damages are excluded from the model. By 2200, damages have reduced income per capita by 77%. These projections are much higher than others found in the IAM literature (Tol, 2014; Tol, 2015), e.g., the DICE 2007 model predicts a 3% reduction in income for a 3.1 °C increase by 2100 and an 8% reduction for a 5.3 °C increase by 2200 (Nordhaus, 2014). However, these results are consistent with other studies that have used the Weitzman damage function (e.g., Dietz and Stern (2015)). If the

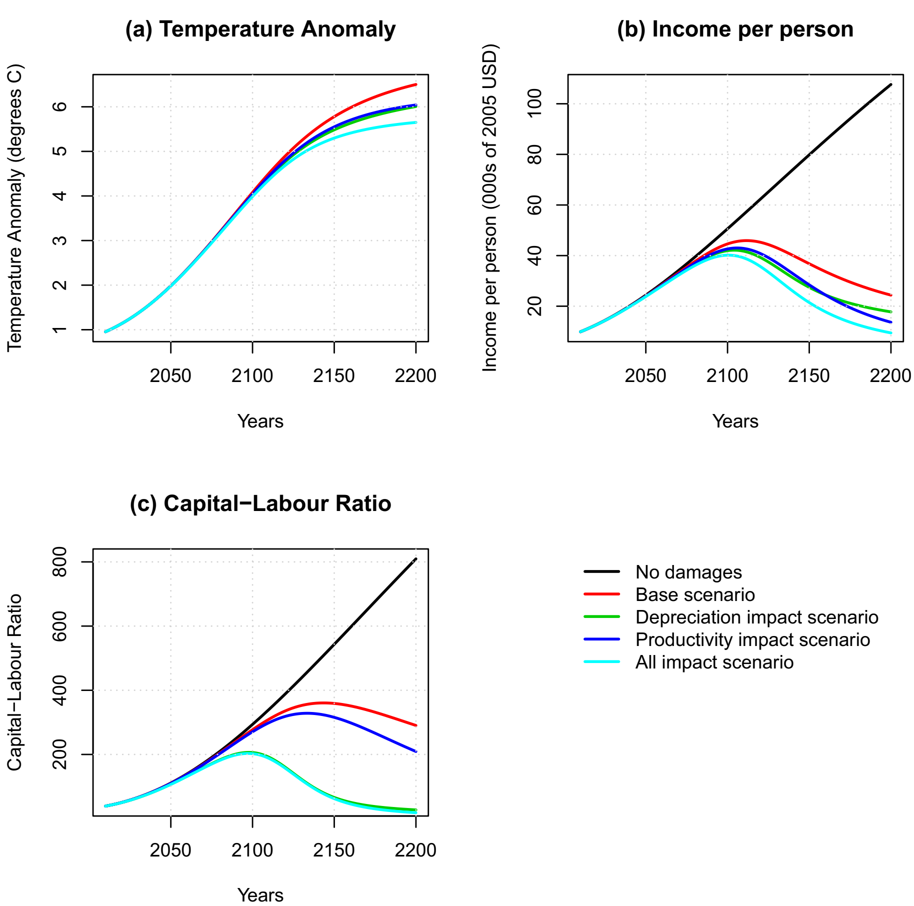


Fig. 1. Projections.
Notes: The results are for simulations when the elasticity of substitution between capital and labour, σ, is equal to 1, i.e., the Cobb-Douglas case. The black lines are from simulating the model with no climate damages. The Base Scenario (in red) refers to a damage function that is multiplicative on the level of production. The Productivity Impact Scenario (in blue) has temperature anomaly directly impacting the growth rate of labour productivity. The Depreciation Impact Scenario (in green) has temperature anomaly directly impacting the depreciation rate of the capital stock. The All Impacts Scenario (in teal) is when the damages affect both the depreciation rate and productivity growth. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

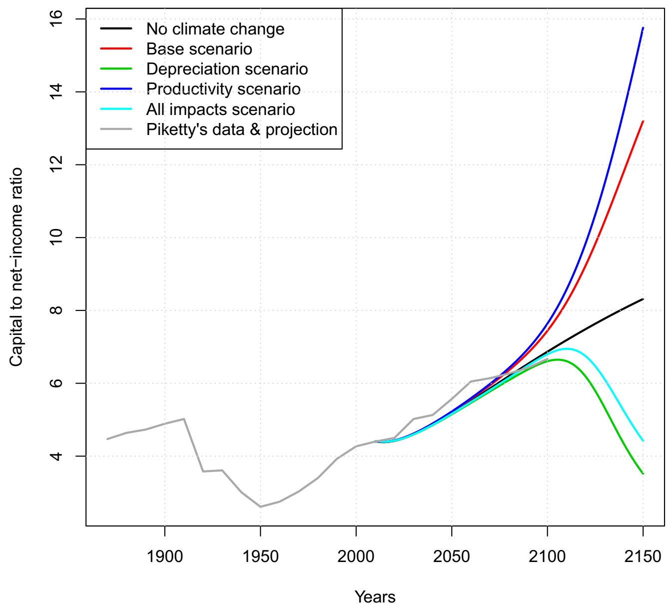


Fig. 2. Historical and projected capital to net-income ratios.
Notes: The results are for simulations when the elasticity of substitution between capital and labour, σ, is equal to 1, i.e., the Cobb-Douglas case. The black lines are from simulating the model with no climate damages. The Base Scenario (in red) refers to a damage function that is multiplicative on the level of production. The Productivity Impact Scenario (in blue) has temperature anomaly directly impacting the growth rate of labour productivity. The Depreciation Impact Scenario (in green) has temperature anomaly directly impacting the depreciation rate of the capital stock. The All Impacts Scenario (in teal) is when damages affect both the depreciation rate and productivity growth. "Piketty's data & projection" (in grey) is reproduced from Piketty (2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

standard DICE damage function is used (as in Appendix A), the results are in-line with others in the IAM literature.

Fig. 2 plots the historical k/y^{net} data and projections from Piketty (2013). In the Base Scenario simulations and using the Cobb-Douglas production function, our projection for k/y^{net} is initially lower than Piketty's, but eventually surpasses his projection in the later part of the 21st century. World capital is 4.4 times net income in 2010, reaches 7.4 times in 2100 and, is > 12 times by 2150. These projections are higher than Piketty's central scenario of world capital approaching 7 times world income by the end of the twenty-first century.[12]

The first three rows of Table 2 include the results using different assumptions about the elasticity of substitution between capital and labour in the CES production function. Two additional CES simulations are considered, one in which $\sigma = 1.3$ and $\alpha = 0.21$, and one in which $\sigma = 0.9$ and $\alpha = 0.35$.[13] Using values of σ that are greater than one slightly dampens the magnitude of the income loss by 2100 in the Base Scenario (7% income loss rather than 11%); whereas, using a value of σ less than one increases the magnitude to a 16% loss of income. The value of the k/y^{net} ratio in 2100 changes with different values of σ in the Base Scenario; however, it also changes in the absence of climate change. Overall, a higher value of σ results in a k/y^{net} ratio in 2100 that is closer to what it would be in the absence of climate change.

Fig. 3a shows the share of income to capital net of depreciation for the Cobb-Douglas production function (red line). Since the gross share is constant the net share will decline as the capital to income ratio increases. The net share declines much more in the Base Scenario than when there is no climate change. The net share starts from 21.8% in 2010, falls to 16.1% by 2100 and reaches −2.6% by 2200 which implies that the marginal productivity of capital has declined to such a degree that it is less than the depreciation rate of capital in 2200 (red line in Fig. 3a).[14] Fig. 3b shows the net share for the CES production function with $\sigma = 1.3$. The net share of income to capital in the Base Scenario also declines for $\sigma = 1.3$.[15] Table 2 shows the percentage change in the net share in the Base Scenario as compared to the net share with no climate change for 2100. For 2100 the smallest loss in the net share relative to no climate change is when $\sigma = 1.3$ with a 3.8 % loss, while with $\sigma = 0.9$ the loss in the share of income to capital is 9%. As is evident in Fig. 3, for $\sigma = 1$, $\sigma = 1.3$ and, $\sigma = 0.9$ the net share is lower in the Base Scenario than in the absence of climate change.

Table 2
Sensitivity to elasticity of substitution. Values in 2100.

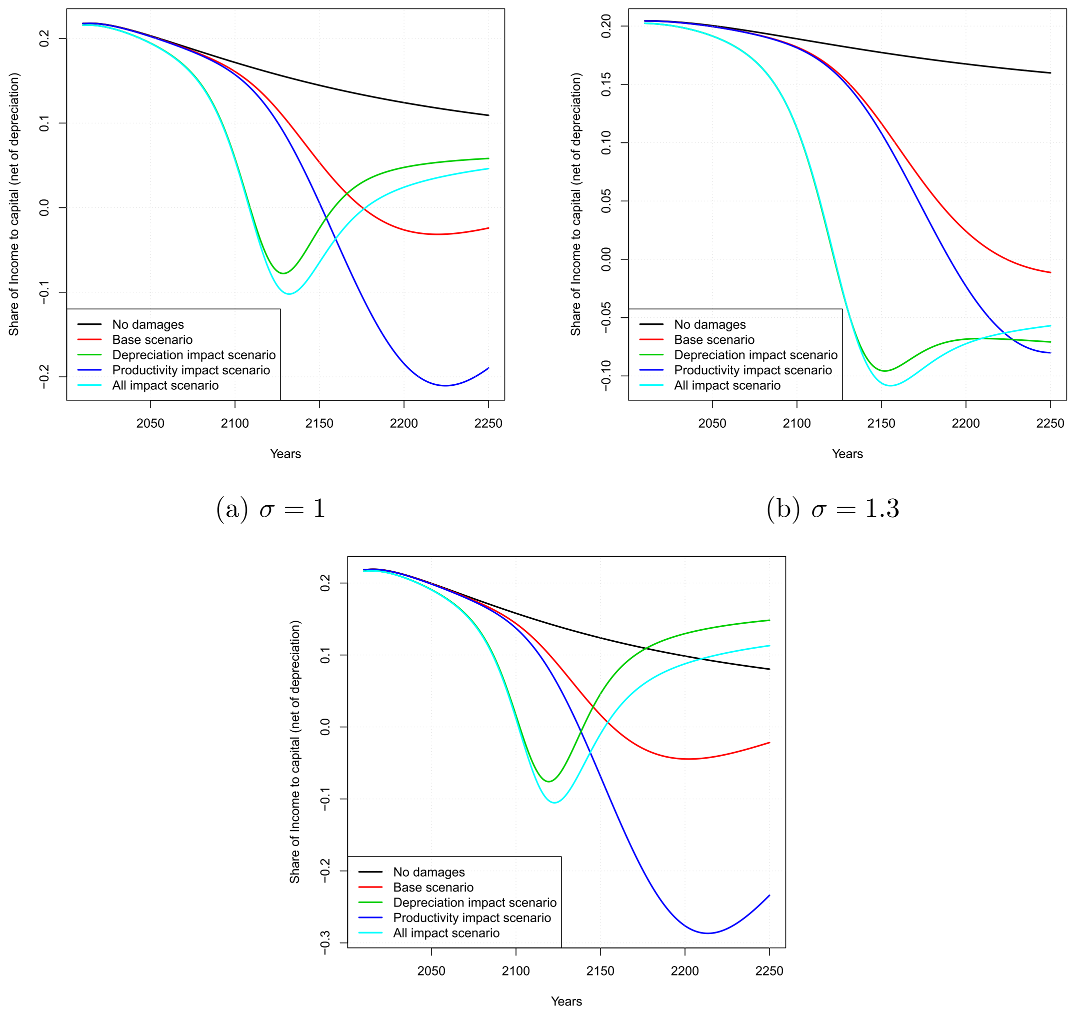
Scenario	Change in income per capita	Change in capital-to-net income ratio	Change in net income share
Base Scenario			
$\sigma = 0.9$	−15.8%	12.1%	−9.0%
$\sigma = 1$	−11.8%	8.5%	−6.3%
$\sigma = 1.3$	−7.0%	4.3%	−3.8%
Productivity Impact Scenario			
$\sigma = 0.9$	−20.4%	15.9%	−13%
$\sigma = 1$	−15.7%	11.2%	−8.4%
$\sigma = 1.3$	−9.9%	6.1%	−4.1%
Depreciation Impact Scenario			
$\sigma = 0.9$	−21.7%	−4.4%	−90%
$\sigma = 1$	−17.1%	−3.8%	−66%
$\sigma = 1.3$	−11.2%	−3.5%	−41%

Notes: Change in income per capita is the percentage reduction in income per capita in 2100 compared to no climate change in 2100. Change in the capital-to-net income ratio is the percentage change in the ratio in 2100 compared to no climate change. Change in net income share is the change in the share of income to capital net of depreciation in 2100 compared to no climate change. The Base Scenario refers to a damage function that is multiplicative on the level of production. The Productivity Impact Scenario has temperature anomaly directly impacting the growth rate of labour productivity. The Depreciation Impact Scenario has temperature anomaly directly impacting the depreciation rate of the capital stock. σ is the elasticity of substitution between capital and labour in a CES production function. When $\sigma = 1$ we use a Cobb-Douglas production function. When $\sigma = 1.3$ we also change α to 0.21 and when $\sigma = 0.9$ we change α to 0.35 in order to have a similar gross share of income to capital as in the Cobb-Douglas case.

3.2. Productivity Impact Scenario results

As in Dietz and Stern (2015), by setting $f_A > 0$ in Eq. (5) we can incorporate the direct impact of climate change on productivity. We simulate our Productivity Impact Scenario using $f_A = 0.05$ (as suggested by Moyer et al. (2014) and Dietz and Stern (2015)) and the values from Table 1. Our simulations indicate that the capital-to-net income ratio will increase more than the increase in the Base Scenario. This effect is shown in Fig. 2 where the ratio in the Productivity Impact Scenario (the blue line) is higher than the ratio in the Base Scenario (the red line) at all points into the future. By 2100 world capital is 7.6 times world net-income and by 2200 capital is over 25 times net-income.[16]

[12] See page 195 of *Capital in the Twenty-First Century* by Thomas Piketty.
[13] The value of α is changed in order for the initial value of the gross share of income to capital to be around 0.3. In the Cobb-Douglas simulations, the gross share of income to capital remains constant and is equal to 0.3.
[14] Although the marginal product of capital falls initially as k/y^{net} increases eventually it starts rising as k/y^{net} falls and rising above the depreciation rate and the share of income accruing to capital stabilizes at 5.1% in the very long run (year 2500).
[15] In the very long run (2500) the net share of capital stabilizes at 1.5%.
[16] After 2200 the ratio starts falling and stabilizes in the very long run, in year 2500, below 15.



(a) $\sigma = 1$

(b) $\sigma = 1.3$

(c) $\sigma = 0.9$

Fig. 3. Share of income to capital net of depreciation.
Notes: σ refers to the elasticity of substitution between capital and labour. Panel (a) is the Cobb-Douglas case with the same scenarios as in Figs. 1 and 2. Panel (b) is from simulations using CES production and the same damage scenarios, but with $\sigma = 1.3$. Panel (c) is from simulations using CES production and the same damage scenarios, but with $\sigma = 0.9$. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

The top left graph in Fig. 1 shows that temperature anomaly is slightly lower in the Productivity Impact Scenario than in the Base Scenario. The underlying reason this occurs is due to the negative impact of temperature anomaly on income per capita which in turn reduces future emissions and thus reduces the growth path of cumulative emissions. The top right graph in Fig. 1 also shows very large effects on income per capita: reducing it by 15.7% in 2100 relative to no climate change.

The impact of climate change on productivity causes an inverted-U shape on capital per worker/person over time (see Fig. 1), just like its impact on income per person. However, the impact of climate change on productivity affects income per person more than it affects capital per person which in turn increases the capital-to-income ratio above the Base Scenario path. Hence, the capital-to-income ratio rising is due to income per person rising slower than capital per person in the earlier time period before they peak causing possible concern of rising wealth inequality but after its peak around 2100 the rise in the capital-to-net income ratio is due to income falling faster than capital is falling.

The middle three rows of Table 2 contain results for the Productivity Impact Scenario using the CES production function for different values of the elasticity of substitution. When the elasticity of substitution is higher ($\sigma = 1.3$), income loss in 2100 is less (10%) relative to Cobb-Douglas (15.7%). When the elasticity of substitution is lower ($\sigma = 0.9$), income loss in 2100 is larger (20.4%). A similar result is shown for the k/y^{net} ratio in 2100: it is larger with $\sigma = 0.9$ and smaller with $\sigma = 1.3$. Although changing the value of σ affects the value of the k/y^{net} ratio, it does not change the overall direction of the ratio, i.e., in the Productivity Impact Scenario the k/y^{net} ratio is everywhere above the k/y^{net} ratio of the Base Scenario regardless of the value of σ.

The share of income to capital net of depreciation is shown in Fig. 3 as well as for 2100 in Table 2. The net share declines as compared to no climate change regardless of the value of σ. The net share also is lower than in the Base Scenario for all σ values considered over the next 200 years.[17] Comparing Fig. 3a and b, we see the net share declining much more when $\sigma = 1$ compared to when $\sigma = 1.3$.

In summary, we can conclude that capital owners will suffer a reduction in capital (wealth) and in their net share of income if climate change adversely affects labour productivity. This is despite a capital to net income ratio increasing over the next 200 years; the increase is due to income falling faster than the fall in stock of capital after 2100.

[17] For $\sigma = 1$ the net share in the very long run equals the base case of 5.1%. For the other two cases of σ and in the very long run it converges to 5.3%.

3.3. Depreciation Impact Scenario results

To allow for climate damages to impact the capital stock, we follow Dietz and Stern (2015) and set f^K equal to 0.3 for our simulations.[18] This apportions the damage function (Eq. (7)) between the production function (Eq. (1)) and the equation of motion for the capital stock (Eq. (2)). To calculate the capital to net income ratio and the net share of income, we calculate the following effective depreciation rate in this scenario as

$$\hat{\delta}_t = \delta_K + D_t^K - \delta_K D_t^K. \tag{14}$$

The projected path of the k/y^{net} ratio in the Depreciation Impact Scenario is visible in green in Fig. 2 alongside the other scenarios. The ratio increases at first, but eventually peaks at 6.6 near the end of the 21st century, and then begins to decrease. By 2250 it has fallen to 1.8 which is much lower than the initial value in 2010.[19] The ratio is increasing at first, when temperature anomaly is < 4 °C, because net income increases at a slower rate than the stock of capital. However, during the next century net income per person starts falling at a slower rate than the stock of capital is being destroyed and this drives the capital-to-net income ratio to fall below 2010 levels by 2150. In short, increased depreciation is the capitalist's worst enemy.

The Depreciation Impact Scenario shows a large effect on income per capita. By 2100 the reduction in world income per person is 17% lower than in the absence of climate change. Income per capita then begins to decline soon past 2100.

As can be seen in Fig. 1, the Depreciation Impact scenario has a large impact on the capital-labour ratio. When temperature anomaly affects the depreciation of capital, the K/L ratio increases initially but starts falling sooner and at a much faster rate relative to the Base and Productivity Impact Scenarios. The climate change impact on depreciation of capital affects capital per person much more dramatically than it affects income per person. The impact on capital per person arising from temperature anomaly affecting depreciation in 2100 and 2250 is a 30% and 97% reduction relative to no climate change. Contrasting with the reduction in income per person in 2100 and 2250 of 17% and 84% respectively indicates that the capital per person growth rate at any time period is lower than the income per person growth rate resulting in an eventual reduction in the capital-to-income ratio.

The last three rows of Table 2 show results for the Depreciation Impact Scenario using the CES production function for different values of the elasticity of substitution. Similarly to the Base Scenario and the Productivity Impact Scenario, when the elasticity of substitution is higher ($\sigma = 1.3$) income loss in 2100 is less than when the elasticity of substitution is lower ($\sigma = 0.9$), income loss in 2100 is larger (i.e., 11.2 versus 21.7 percent loss). As for the k/y^{net} ratio in 2100, it is smaller with $\sigma = 0.9$ and larger with $\sigma = 1.3$. Similarly to the Productivity Impact Scenario, although changing the value of σ affects the value of the k/y^{net} ratio, it does not change the overall direction of the ratio, i.e., in the Depreciation Impact Scenario the k/y^{net} ratio is everywhere below the k/y^{net} ratio of the Base Scenario regardless of the value of σ.

The share of income to capital net of depreciation is shown in Fig. 3a, b, and c as well as for 2100 in Table 2. The net capital share is drastically lower than in the absence of climate change regardless of the value of σ. The lower is σ, the larger is the decline in the net-share. Comparing Fig. 3a and b, we see the net share declining drastically regardless of whether σ is equal to 1 or 1.3 until around 2150 after which the net share starts rising again.[20] The initial decline is due to the large increase in the effective depreciation rate due to climate change. However, the eventual upturn in the net share is due to the marginal productivity of capital eventually rising as capital per gross output eventually falls.

3.4. All Impacts Scenario results

In a final scenario, we apportion damages across all three possible impact channels, i.e., we set $f_A = 0.05$ and $f_K = 0.3$.

Given that the depreciation impact reduces the capital-to-net income ratio and the productivity impact operates in the opposite direction; the net effect on the capital-to-net income ratio is ambiguous. For our selected values of f_A and f_K, the effect on depreciation completely outweighs the effect on productivity and the ratio is lower in the All Impacts Scenario (the teal line in Fig. 2) than in the absence of climate change.

It is apparent in Fig. 1 that the All Impacts Scenario closely follows the Depreciation Impact Scenario. The All Impacts Scenario produces the largest impacts on income per capita out of the four scenarios considered. As listed in Table 2, income per capita is 20.6% lower in 2100 than with no climate change; whereas, in the Depreciation Impact scenario it is 17.1% lower and in the Productivity Impact scenario it is 15.7% lower. The loss in world income per person in the All Impacts Scenario is similar to the projection of Burke et al. (2015) of a world income per person loss of 23% by 2100.

Temperature anomaly is relatively close across the four scenarios (see Fig. 1). It is highest in the Base Scenario and lowest in the All Impacts Scenario. This is due to the differing impacts on income per capita: lower income per capita results in lower cumulative emissions via Eqs. (8) and (9).

4. Emissions abatement scenarios

In both the Depreciation Impact Scenario and the All Impacts Scenario, the capital-to-net income ratio is lower than in the absence of climate change. This outcome may represent a quite dismal result since a successful attempt to hold temperature rise to 2 °C might lead to a higher capital-to-net income ratio, an indicator of importance for inequality, than business as usual; although, not in terms of the net capital share which will be less than business as usual.[21] In this section we add emissions abatement to the model and examine the effect on the capital-to-net income ratio and the net share of income to capital. We consider two possible abatement scenarios: One that holds temperature change to 2 °C above pre-industrial and one that puts no restriction on temperature change.

When emissions abatement is included, annual emissions are determined by

$$E_t = [1 - M_t]\mu_t Y_t, \tag{15}$$

where M_t is the emission control rate in year t. Following Nordhaus and Sztorc (2013), abatement cost is represented as $\phi_t M_t^2$ and the abatement cost coefficient, ϕ declines over time at the same rate that A increases. The resulting total output adjusted for abatement cost and climate damages when σ is equal to one is[22]:

$$Y_t = [1 - \phi_t M_t^2](1 - D_t^Y)(A_t L_t)^{(1-\alpha)} K_t^{\alpha}. \tag{16}$$

For the 2 °C Abatement Scenario, we assume that a social planner chooses emissions abatement to maximize the discounted sum of utility from $t = 0$ to $T = 491$ (2500) subject to the restriction that

[18] For our depreciation impact scenario, $f_A = 0$.

[19] The ratio remains at this low value in the very long run.

[20] In the very long run and with $\sigma = 1$ the net share reaches 6.7%, while with $\sigma = 1.3$ the net share rises but stabilizes at −7.3%. Finally in the case of $\sigma = 0.9$ it stabilizes at 16.5% in the very long run.

[21] A higher capital to income ratio will reduce the net capital share relative to BAU.

[22] It should be noted that we (and Nordhaus and Sztorc (2013)) are assuming that abatement affects capital and labour equally. However, this may not be an entirely accurate assumption, for example, renewable sources of energy, e.g., solar, are more capital intensive than conventional sources of energy.

$\beta C_0 + \beta \Sigma_{i=0}{}^T E_i = 2$, i.e.,

$$\max_{\{M_t\}_{t=0}^T} W = \sum_{t=0}^{T} u(c_t) L_t (1+\rho)^{-1}, \tag{17}$$

where $u(c_t)$ is utility of consumption per capita at time t and ρ is the utility rate of discount. We use the same iso-elastic utility function as Nordhaus and Sztorc (2013) and Dietz and Stern (2015), where $u(c_t) = C_t^{1-\eta}/(1-\eta)$. Following Nordhaus and Sztorc (2013) and Dietz and Stern (2015) we set ρ = 0.015 and $\eta = 1.5$.

We do the same maximization problem for the Optimal Abatement Scenarios, but without the restriction on temperature change.[23]

The results for the Base Scenario, Depreciation Impact Scenario, Productivity Impact Scenario, and the All Impacts Scenario for 2100 are shown in Table 3. The results for the two abatement scenarios are relatively similar; however, the 2 °C constraint does bind when implemented, suggesting that the optimal temperature change is above 2 °C in all scenarios considered.[24] For both the 2 °C Abatement Scenario and the Optimal Abatement Scenario, emissions abatement mitigates the substantial income losses incurred in all of the four climate impact scenarios from the previous section. For example, in the Base Scenario, income per capita in 2100 is 8.9% higher in both abatement scenarios as compared to Business-as-Usual (BAU), i.e., no abatement. Furthermore, as can be seen in Fig. 4a and b, emissions abatement leads to a capital-to-net income ratio that closely follows the ratio from the no climate change case, regardless of the climate impact scenario. For example, in the Productivity Impact Scenario, emissions abatement leads to a much lower capital-to-net income ratio by 2100 as compared to BAU (a ratio of 6.94 rather than 7.6). In the Depreciation Impact Scenario, emissions abatement leads to a higher capital-to-net income ratio in 2100 than when there is no emissions abatement (6.7 rather than 6.6). Emissions abatement has a moderating effect on the capital-to-net income ratio by reducing future temperature change (and future damages) and moves the ratio back towards where it would be in the absence of climate change (6.87 in 2100). This would bring the net capital share closer to the share in the absence of climate change which is the highest level relative to any of the climate change scenarios explored in this paper. For 2100 the net capital share is higher with abatement than without abatement for all scenarios (see the last column of Table 3). Abatement, even though costly, will benefit all stakeholders, including the owners of capital, and will stop income per capita from falling. Climate change if left unmitigated, and if it adversely affects the growth rate of labour productivity, will have severe consequences on the two indicators of inequality examined in this paper.

5. Conclusion

We focused on two indicators of importance for inequality, the global capital-to-net income ratio and the net capital share of income. If climate change impacts capital depreciation, then the capital-to net income ratio eventually decreases over the next 200 years to levels not seen since the end of World War II due to the destruction of capital. If climate change instead impacts productivity growth, then the capital to net-income ratio increases. Initially the increase, in the Base Scenario and the Productivity Impact Scenario, is due to income increasing at a slower rate than capital, as is predicted by Piketty during this century; however, after 2100 the increase is from income decreasing at a faster rate than capital. The world's standard of living as measured by income per capita will be significantly lower than in the absence of climate change in all scenarios by 2200 due to the highly convex damage function. The world's capital per worker will be significantly lower when climate change affects the stock of capital. In terms of the net share of income to capital, climate change will lead to a lower net income share for all cases relative to no climate change with the most dramatic reductions occurring when it impacts depreciation and $\sigma = 1.3$.

From a policy perspective, Piketty argues for a wealth tax to reduce the global wealth-to-net income ratio and reduce the wealth inequality which was observed over the last 30 years and predicted to continue to the end of this century. Although Piketty associates a high capital-to-net income with "large world instability, asset price bubbles, and a high degrees of inequality" we find that a low or a high capital-net income ratio by 2100 and beyond due to unmitigated climate change will be a result of the relative decline in the amount of capital each person has at their disposal and the resulting lower standard of living as measured by net income per capita. Our simulations suggest that climate change will impact the capital-to-net income ratio in ways that are unprecedented; these unprecedented changes might result in global political instability and inequality as well as potential collapses in asset prices. Abatement to keep temperature anomaly to 2 °C will mitigate the substantial losses to the standard of living, reduce world instability and inequality and avoid the collapse of asset prices. In this sense, it is in the best interest of capital owners to support policies such as a world carbon tax or an emissions trading system to avoid dangerous climate change impacts.

One limitation of our model and analysis is that we follow Dietz and Stern (2015) and Piketty (2013) and assume a constant rate of savings. The savings rate may be affected by climate-induced changes to the real rate of return on capital, which in turn depends on the marginal product of capital net of the depreciation rate. In our Depreciation Impact Scenario, as in Dietz and Stern (2015) and Bretschger and Karydas (2018), climate change will increase the depreciation rate. The effect of this change on the savings rate is ambiguous. Capital destruction due to climate change will reduce the stock of capital, which in turn increases the marginal product of capital, thus encouraging more savings. On the other hand, the increased depreciation rate will reduce the net-return to capital ($MP^K - \hat{\delta}$), holding MP^K constant, reducing the incentive to save. If the net effect was to increase the savings rate (as in Bretschger and Karydas (2018)), then investment would increase and, due to our mechanism of endogenous growth, slow the decline in productivity growth. It is uncertain how these changes (i.e., savings rate increasing and improvement in productivity growth) will impact projections for the capital-to-net income ratio in this scenario.

The effect of climate change on the savings rate in our Productivity Impact Scenario is also ambiguous. A lower productivity growth rate will increase the marginal productivity of capital in the future, relative to the current marginal product, due to labour being less effective in the future; this effect discourages savings today. However, a lower growth rate implies less consumption in the future relative to current consumption. As a result, households may desire to increase their savings rate to make up some of the lost future consumption. The total effect would depend on the elasticity of marginal utility of consumption. A high elasticity would encourage savings and vice versa. The potential encouragement of savings would operate to offset some of the reduction on the growth rate of labour productivity due to the direct impact of climate change. An avenue for future research should be to determine how an endogenous savings rate will impact the capital-to-net income ratio and the share of net income accruing to capital.

An additional potential limitation of our paper is that we do not formally model fossil fuel extraction in a way that is consistent with the economics of non-renewable resources. In addition, we have not considered the impact of climate change on natural capital. Climate change will adversely affect the stock of natural capital and the functioning of ecosystem services (Hoegh-Guldberg and Bruno, 2010; Hansen et al.,

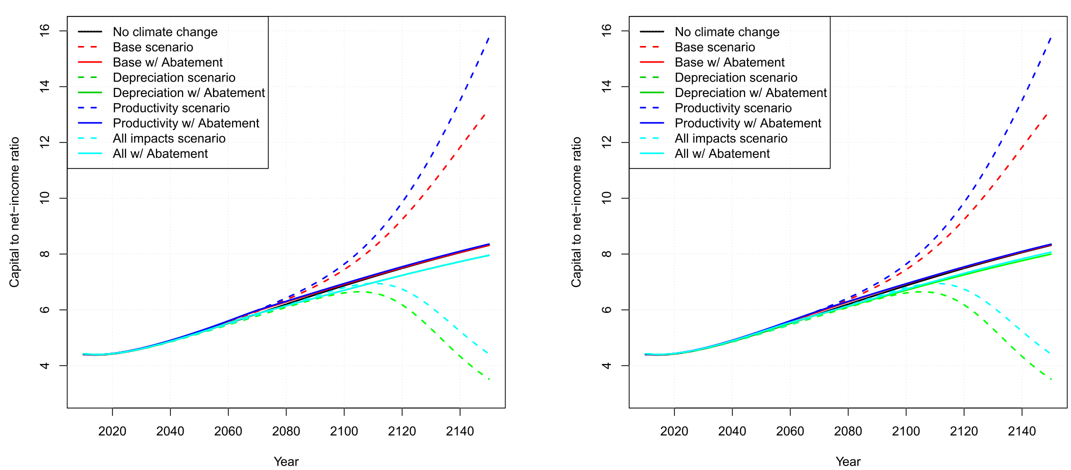
[23] The optimization was conducted in R using the alabama package for constrained nonlinear optimization developed by Varadhan and Grothendieck (2015).

[24] The level of temperature anomaly values listed in Table 3 is only for the year 2100. In all of the optimal abatement scenarios, temperature anomaly continues to rise after 2100.

Table 3
Emissions abatement scenario results. Values in 2100.

Scenario	Temp. anomaly	Change in income as % of BAU	Capital-to-net income ratio	Net share to capital
Base Scenario				
No abatement	4.08	0%	7.4	16.1%
2 °C abatement	1.99	+8.9%	6.9	17.1%
Optimal abatement	2.17	+8.9%	6.9	17.1%
Productivity Impact Scenario				
No abatement	4.03	0%	7.6	15.7%
2 °C abatement	1.91	+12.4%	6.9	17%
Optimal abatement	1.87	+12.4%	6.9	17%
Depreciation Impact Scenario				
No abatement	4.02	0%	6.6	5.8%
2 °C abatement	1.96	+11.3%	6.7	16.3%
Optimal abatement	1.73	+13.7%	6.7	16.3%
All Impacts Scenario				
No abatement	3.99	0%	6.8	5.6%
2 °C abatement	1.96	+16.3%	6.7	16.3%
Optimal abatement	1.58	+18.1%	6.7	16.7%

Notes: The table shows results for simulations where emissions abatement is added to the model. The social planner chooses the annual levels of emissions abatement to maximize the present value of the sum of utility from 2010 to 2500. 2 °C abatement refers to the simulations with optimal emissions abatement under the restriction that temperature anomaly cannot exceed 2 °C. Optimal Abatement refers to the simulations with optimal emissions abatement without the temperature restriction. The simulations use an elasticity of substitution equal to one.



(a) 2°C emissions abatement (b) Optimal emissions abatement

Fig. 4. Capital to net-income ratios with emissions abatement.
Notes: Please see notes for Table 3.

2013). Climate change may also affect the distribution of natural capital. For example, fish stocks may shift towards the poles; therefore, making wealth inequality worse as this represents a reallocation of natural capital from relatively poorer countries to relatively richer countries (Fenichel et al., 2016). There is also the differing incidence of climate damages between rich countries and poor countries. For example, areas where a larger percentage of the population live in rural poverty are expected to suffer higher mortality impacts (Burgess et al., 2017). We leave these important issues for future research.

Appendix A. Nordhaus damages

This appendix contains results from replicating our Cobb-Douglas ($\sigma = 1$) simulations from the body of the paper with one change, we use the standard DICE damage function, i.e.

$$D_t = 1 - \frac{1}{1 + \theta_1 T_t^2}. \tag{A.1}$$

This is equivalent to setting θ_2 in Eq. (7) as zero rather than 5.07029×10^{-6}. As can be seen in Table A.1, using the standard DICE damage function reduces the magnitude of the impacts in 2100, but it does not alter the sign of the impacts. Fig. 1 is replicated using the different damage function and is displayed in Fig. A.1. Similarly, as displayed in Fig. A.2, the direction of the k/y^{net} ratio is unchanged; climate impacts on productivity growth increase the ratio above what it would have been otherwise, and climate impacts on capital depreciation decrease the ratio below what it would have been otherwise. Fig. A.3 shows that when we use Nordhaus damages, climate damages cause the chare of income that accrues to capital net of depreciation to decrease as compared to no climate change; however, in none of the scenarios does it now become negative, as it does when Weitzman damages are used.

Table A.1
Sensitivity to damage function. Values in 2100.

Scenario	Change in income per capita	Change in capital-to-net income ratio	Change in net income share
Base Scenario			
Weitzman damage, $\theta_2 = 5.07029 \times 10^{-6}$	−11.8%	8.5%	−6.3%
Nordhaus damage, $\theta_2 = 0$	−5%	2%	−1.7%
Depreciation Impact Scenario			
Weitzman damage, $\theta_2 = 5.07029 \times 10^{-6}$	−17.1%	−3.8%	−66%
Nordhaus damage, $\theta_2 = 0$	−8.9%	−5.4%	−22%
Productivity Impact Scenario			
Weitzman damage, $\theta_2 = 5.07029 \times 10^{-6}$	−15.7%	11.2%	−8.4%
Nordhaus damage, $\theta_2 = 0$	−7.9%	3.9%	−2.9%

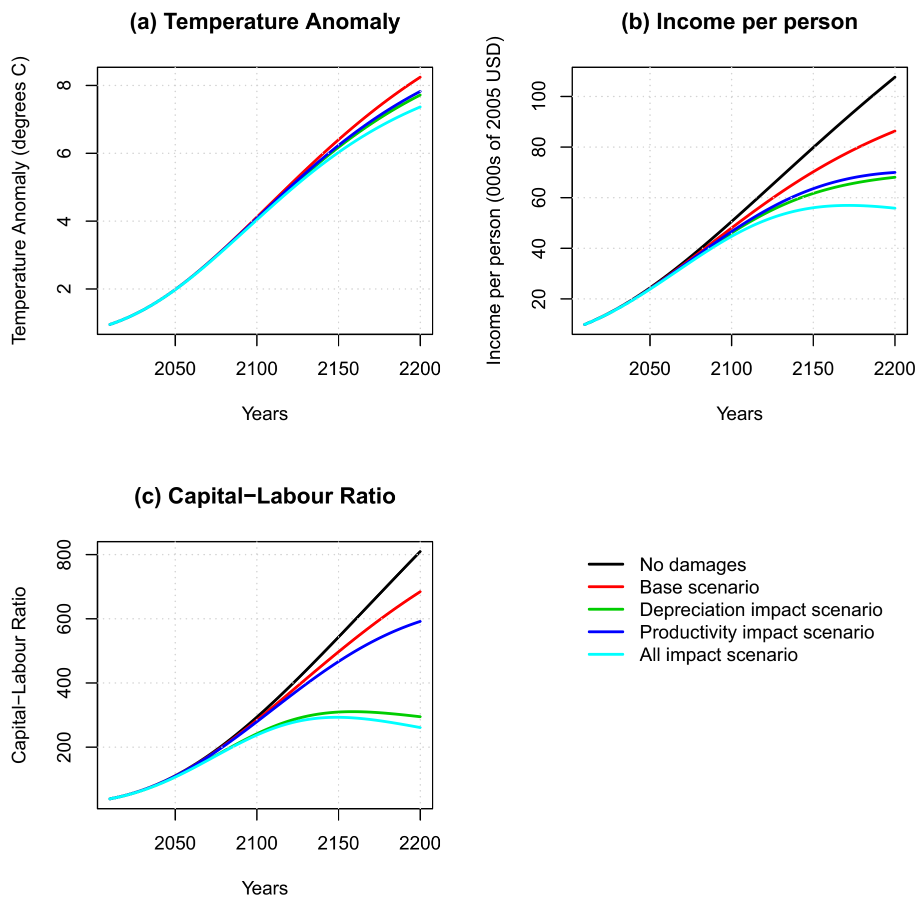


Fig. A.1. Projections: Nordhaus damages.
Notes: This figure replicates Fig. 1 except that it uses the Nordhaus damage function rather than the Weitzman damage function.

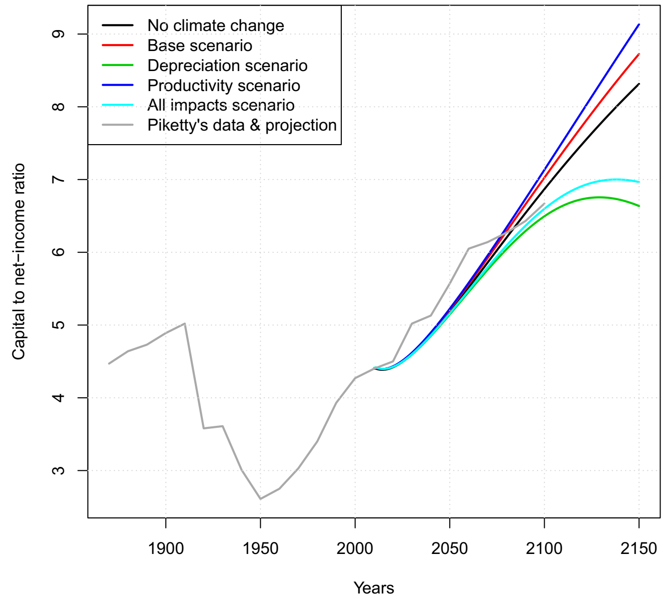


Fig. A.2. Historical and projected capital to net-income ratios: Nordhaus damages.
Notes: This figure replicates Fig. 2, except that it uses the Nordhaus damage function rather than the Weitzman damage function.

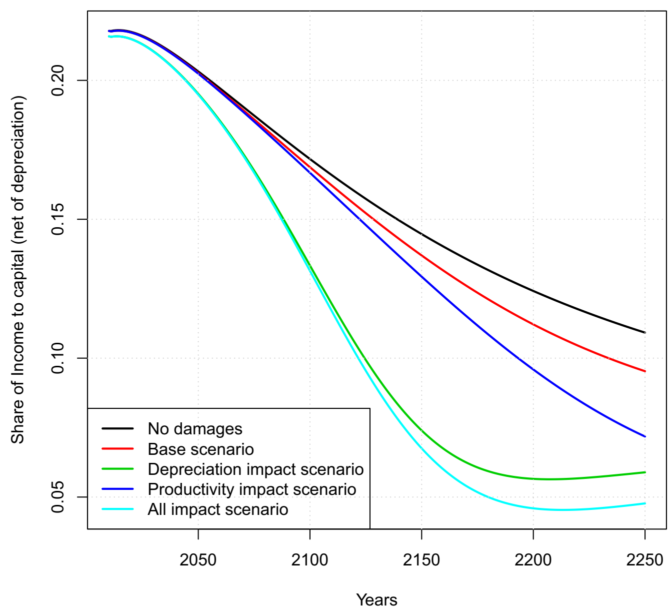


Fig. A.3. Share of Income to capital net of depreciation: Nordhaus Damages.
Notes: This figure replicates Fig. 3a, except that it uses the Nordhaus damage function rather than the Weitzman damage function.

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